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Finite element analysis of impact between cricket ball and cantilever beam

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Abstract

This paper presents an explicit finite element analysis of a cricket ball impacting against a cantilever beam. The model was developed using ABAQUS and was defined in accordance with experimental data. The model is used to determine contact properties associated with impact between cricket balls and sports equipment such as helmets. The developed model was validated through experimental impact tests where the ball was made to impact a cantilever beam at inbound velocities of approximately 17, 23, 38 and 44 m/s. The model's simulation results agreed reasonably well with the experimental results. The friction effects between the cricket ball and the cantilever beam have been considered, and a friction coefficient of 0.2 was adopted for the model. This study is part of a major research project examining the performance of a range of cricket helmets. It is envisaged that the model will be used for design customization and optimization of cricket helmets and other types of protective helmets.

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Keywords: Cricket ball; finite element; contact; impact dynamic; numerical model

1. Introduction

Head and facial injuries are common among cricket players, and are mostly attributed to blunt impacts with the ball [1]. Blunt impact events in cricket can be categorized as low to high velocity impacts (30 <v < 250 m/s) [2], which can cause concussive and other traumatic brain injuries.

Protective sports equipment such as specialized cricket helmets with advanced structures have been found to attenuate the impact energy and hence reduce the incidence of head injury [3]. Recent studies in sports engineering have focused primarily on using finite element (FE) analysis in the design of sports

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equipment to enhance their quality and to reduce the time and cost of development [4-5]. In FE modeling, the dynamic contact problems play an important role in dictating the integrity, performance and safety of many products, such as sports equipment [6].

Obtaining a good estimate of the forces that are transferred through the contact area requires a reasonable choice of contact search algorithm, slave-master surfaces, a thorough material model and coefficient of friction [7-8]. The coefficient of friction pertinent to impact characteristics in cricket ball impacts has only rarely been reported in the literature and is difficult to measure accurately. In order to interpret the simulation results confidently, correct input parameters need to be selected. Minimal research has been reported on FE methods used to investigate the dynamic impact property for headgear such as cricket helmets. This provides a strong motivation to determine the impact properties between the cricket ball and the impacted object under conditions seen in batting. In this paper, FE analysis was used to determine the contact property of a cricket ball model impacting against a cantilever beam.

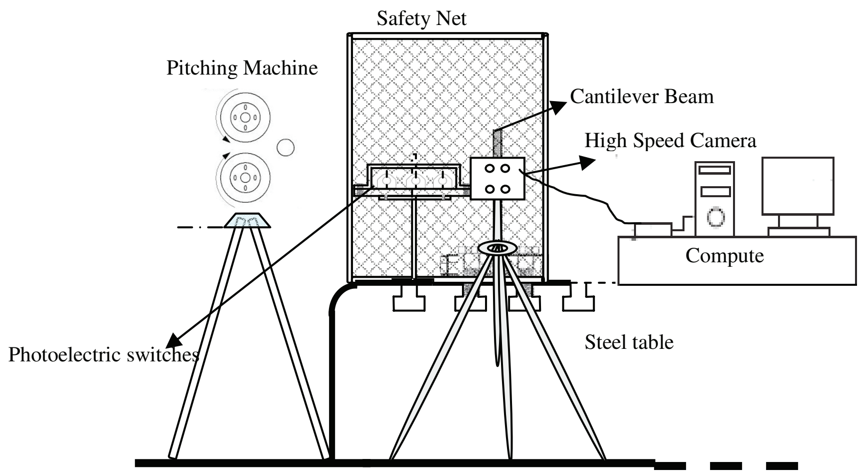

Fig. 1. Schematic diagram of experimental setup.

2. Methods

2.1. Impact test procedures

A schematic set-up of all the equipment used in the experiment is shown in Figure 1. The system consists of a pitching machine, a cantilever beam, a high-speed camera, three photoelectric switches and four uniaxial accelerometers. The professional test series cricket balls have been used in the experimental testing. The cricket balls were fired horizontally from the pitching machine at four different velocities (17, 23, 38 and 42 m/s) aiming to impact the cantilever plate. Each test was repeated five times in order to get achieve statistical significance.

The cantilever beam was made of mild steel and was firmly bolted vertically to a steel table. The impact and rebound velocities of the cricket ball were measured using three photoelectric switches, which were spaced 100 mm apart. Four uniaxial accelerometers were installed at the back corner of the cantilever beam and the acceleration-time tracers of the plate were recorded during the impact. The cantilever beam and photoelectric switches were setup within an enclosure that was made up of metal frames surrounded by a safety net. The ball was captured within the enclosure after the impact. The behavior of the cricket ball and the cantilever beam during and after the impact was recorded using a high-speed camera running at 5000 frames per second (fps).

2.2. Finite element model

The commercially available finite element (FE) program ABAQUS version 6.9 [8] was used for the FE analysis in this study. Due to the short duration, large deformations and nonlinear response during the impact, the ABAQUS/Explicit FE solver was selected for the analysis. Simulation time was set to 4 milliseconds to allow for pre-impact ball motion, the beam-ball impact period and sufficient time to capture the post-impact oscillation of the plate. The solution time step was automatically determined by ABAQUS such that the time increments satisfy the Courant Criterion [9].

The dimensions of the cantilever beam were 500 x 100 x 12 mm and this was modeled as a homogeneous solid with linear elasticity. The plate was discretized into a total of 7392 elements and 10396 nodes. All the elements used in the mesh were 8-node solid elements with each element of the size 5 mm x 5 mm.

The cricket ball model was based on the validated 3-D model published by Cheng [10-11]. It is a universal FE ball model that combines both hyperelastic and viscoelastic properties. It also requires less CPU run-time, making the model suitable for optimization.

2.2.1. Material Properties

The cantilever beam is a ductile metal (mild steel) with a Young's Modulus of 210 GPa, and density of 7.85 gm^{-3}. The Poisson's ratio was assumed to be 0.3. The material property introduced into the analysis was a linear elastic material with the appropriate elastic contacts and loading.

2.2.2. Boundary Conditions

The boundary and loading conditions were set up according to the impact test procedure, i.e. the base of the plate was fully constrained (encastered). The impact velocities of the cricket ball on the cantilever beam were simulated at 17, 23, 38 and 44m/s, which are the average speeds obtained from the experimental tests.

2.2.3. Contact modeling

The ABAQUS general contact algorithm between to deformable bodies with finite sliding was assigned to arbitrarily shaped contact areas [8-9]. The pressure-overclosure contact property that governs the motion of the contacting surfaces was chosen for the contact modeling in the present study. In this method, the contact constraint is applied when the clearance between two surfaces becomes zero. The constraint is removed when the contacting surfaces are separated and the contact pressure between them becomes zero or negative [9]. For contact modeling, the cricket ball and the plate were set as the slave surface and master surface, respectively. The contact properties were considered to be hard and penalty contact.

3. Results

The impact behavior of the cricket ball and cantilever beam was obtained from the computer simulations using ABAQUS. The results of the FE analyses were compared with those from the experiments to confirm the accuracy of the FE models. Figure 2 compares the simulation results, in terms of acceleration-time curves, with those from the experimental work. In general, the model response correlates reasonably well with the experimental results: The contact timing, slopes of the loading and unloading phase, and peak acceleration of the cantilever beam in the simulation were consistent with those in the experimental tests.

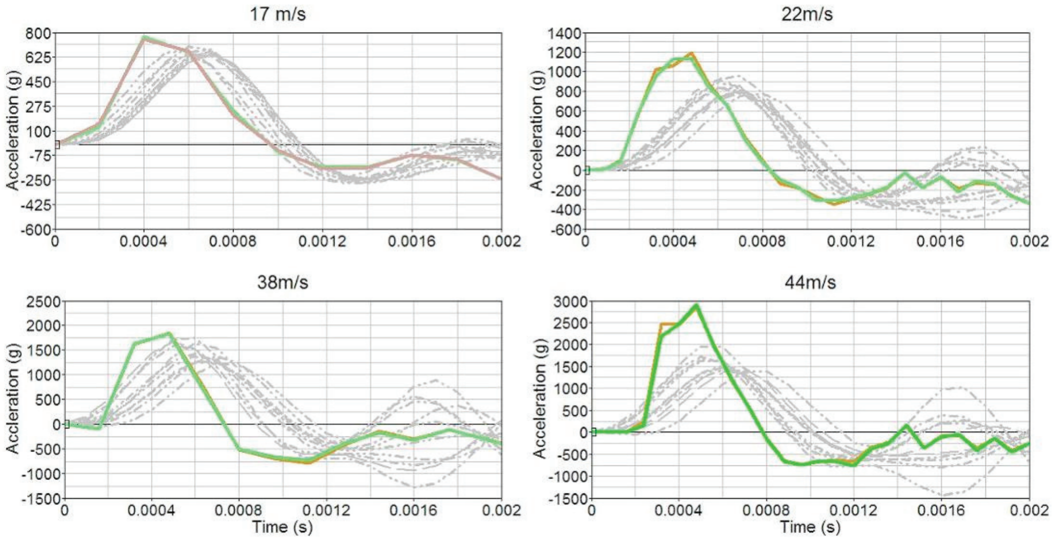

Fig. 2. Experimental (dotted lines) and simulated (solid lines) acceleration-time responses of cricket ball impact against a cantilever beam at four test velocities.

An important result from the dynamic FE analysis between the cricket ball and the cantilever beam is the coefficient of restitution (COR). By definition, the COR in a collision in the normal direction can be calculated using the inbound velocity, v_{in}, and outbound velocity, v_{out}, of the ball. The v_{in} is an input parameter and the v_{out} of the ball is obtained by averaging the velocities of all nodes of the FE mesh immediately after the ball is separated from the cantilever plate. The COR obtained from the experiment and FE analysis are presented in Figure 3.

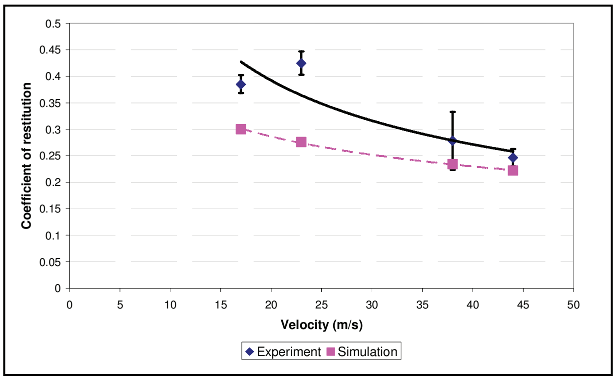

Fig. 3. Coefficient of restitution obtained from experimental work and finite element analysis.

Figure 4 shows an example of images taken from the high speed camera for the impact between a cricket ball and the cantilever beams at 44 m/s. The corresponding numerical results were compared with the experimental images. Good correspondence can be observed between the deformations predicted by the FE model and those recoded by the high speed camera.

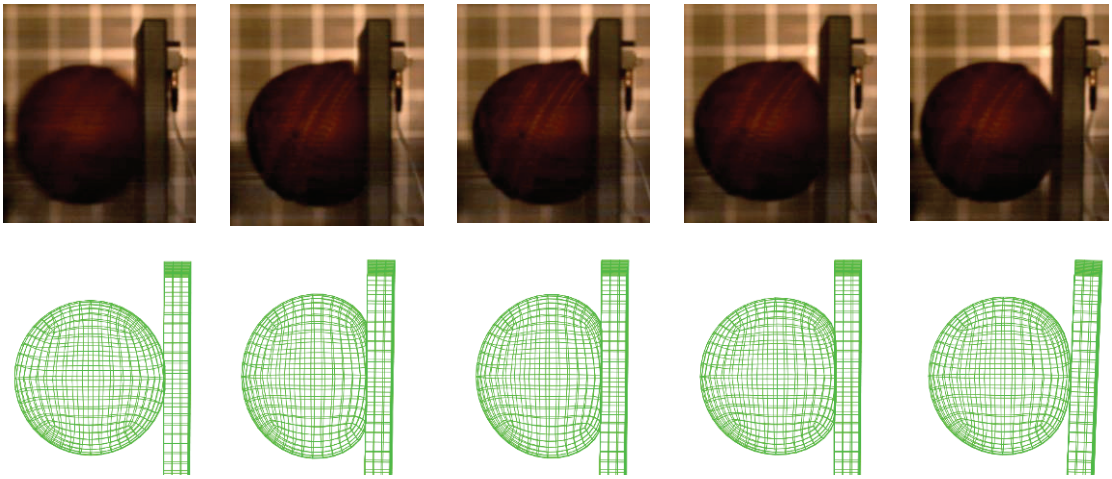

Fig. 4. Example of high speed camera images for an impact test at 44 m/s between a cricket ball impacting with a cantilever beam (top) and the corresponding numerical results (bottom).

4. Discussion

The aim of this investigation was to determine the contact properties of a cricket ball impact against a cantilever beam. Data was acquired using four accelerometers mounted onto the impact beam, photoelectric switches and a high-speed camera running at 5000 fps enable the measurement of COR, accelerations, deformation and contact time. In the FE model, the contact between the cricket ball and the cantilever beam was simulated by adopting the 'penalty method'. Initially, no friction effects were considered in any of the contact interfaces. However, it was necessary to impose friction force for the two contact interfaces of cricket ball and the beam, in order to account for dynamic friction. A friction coefficient of 0.2 was adopted. The overall acceleration-time responses obtained from the experiments and those from the FE model seem in reasonable agreement. Only marginal discrepancy was observed between the experimental and simulated results. The numerical loading phase of the numerical model occurred more quickly than the corresponding experimental ones. The contact duration of the simulation was slightly less than that from the experiment.

The universal cricket ball has adopted the Mooney-Rivlin and viscoelastic models. The Mooney-Rivlin property was to account for the nonlinearity associated with deformations. The viscoelastic model was to represent the time-dependent nature of the ball and to accommodate energy loss associated with the ball speed dependent COR [12]. The COR of the simulated results was validated by comparing the measurement via the photoelectric switches. At the higher impact velocities, the COR of FE analysis are within the standard deviation of experimental tests.

The deformations of the cricket ball have been appropriately predicted by the FE universal cricket ball model. However, some differences can be noticed as the FE model demonstrated a more uniform deformation than that of an actual cricket ball. This is because the cricket ball is a complex nonhomogenous sphere made up of multiple layers (a cork-rubber core, cork-and-twine packing, and a stitched leather cover), whereas the universal FE cricket ball was modeled as homogeneous solids [10]. This might have some influence on the overall deformation behavior of the FE model and caused some discrepancy between the experimental and the numerical results.

Despite some differences have been observed between the experimental results and those from the numerical model, the FE model provide a basis for further application for the simulation involving impact of a cricket ball with other sport equipments.

5. Conclusion

In this research a novel FE model was created to determine the impact behavior and the contact properties of impact between a cricket ball and a cantilever beam. Good agreement was obtained between the numerical simulations and experimental data. The friction effects between the cricket ball and cantilever beam had to be considered, and a friction coefficient of 0.2 was adopted for the model. It is envisaged that the developed FE model can be used as a benchmark reference for impact modeling between cricket balls and sports equipment. The model will be applied as a predictive tool to assist the optimization and development of customized cricket helmets. Also, it will be used to assess impact performance of a range of alternative helmet designs. Hence, the work presented in this paper provides a fundamental developmental platform for design of protective helmets in sports.

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